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A city-level inventory for atmospheric mercury emissions from coal combustion in China

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Highlights:

- An inventory of mercury emissions from coal combustion in 182 Chinese cities was compiled.
- Plant-specific air pollution control devices installation rates in 182 cities were updated.
- 36 cities such as Chongqing and Ordos contributed over half of the total emissions.
- Industrial coal combustion was identified as the dominant source for city-level mercury emissions.
- Dedicated mercury control policies were elaborated for different types of cities.

Keywords: atmospheric mercury, city-level inventory, mitigation policy, coal combustion

Abstract

Cities are essential entities for dedicated mercury control policies. However, the city-level mercury emission inventory as the cornerstone of proper policy design is still in its infancy, due to data availability. For the first time, this study developed a comprehensive city-level atmospheric mercury emission inventory from coal combustion in China in 2010, by updating emission factors based on high-resolution information such as the plant-specific air pollution control devices (APCDs) in 182 cities. The estimated atmospheric mercury emissions from coal combustion were 202.3 tons (-51.7%,133.6%), over half of which were concentrated in 36 cities such as Chongqing (megacity) and Ordos (heavily coal-reliant city), implying mercury emissions were unevenly distributed. Mercury emitted from coal-fired power plants

with the largest coal consumption was less than that from industrial coal combustion, because more efficient APCDs were installed in power plants. This study also took GDP, the proportion of coal in energy mix and cities' population as the benchmark to classify cities into various groups. Energy production and heavy manufacturing cities had comparatively larger emissions. Moreover, optional mitigation policies were elaborated for specific cities, such as retrofit of APCDs for coal-reliant cities (e g., Nanyang and Sanmenxia) lack of enough efficient end-of-pipe mercury removal devices.

Graphical Abstract

1 Introduction

Coal combustion is one of the primary sources for atmospheric mercury, a highly toxic hazard that has adverse impacts on both the ecosystem and human health (Chen et al., 2019; Giang and Selin, 2016; Mergler et al., 2007; Oberschelp et al., 2019; UNEP, 2013). According to the latest Global Mercury Assessment, 22% of global mercury emissions come from coal combustion (UNEP, 2019). In China, the world's largest mercury emitter and coal consumer, mercury emissions from coal combustion account for about 37%-54% of the total mercury emissions (Chen et al., 2017; Liang et al., 2013; Liang et al., 2014; UNEP, 2008; Wu et al., 2018; Wu et al., 2006; Zhang et al., 2012; Zhang et al., 2015). Regarding the prominent role of coal in global mercury emission picture, the Minamata Convention, an international treaty on mercury control, has listed major coal users such as industrial boilers and power plants as key regulatory targets.

To successfully mitigate mercury pollution from coal combustion, the emission

inventory is crucial, as it can not only reveal the key sectors but also provide fundament and guideline for further researches including atmospheric transport and deposition simulation. Therefore, the compilation of mercury emission inventory has been the hotspot in the field of mercury emissions. Additionally, previous studies focusing on atmospheric mercury emission inventories were initially conducted on a global scale (Pacyna and Pacyna, 2002; Pacyna et al., 2010; Streets et al., 2011; Streets et al., 2009; Streets et al., 2017; Streets et al., 2019; Wilson et al., 2006). The United Nations Environment Programme (UNEP) estimated that global anthropogenic mercury emissions were 2220 tons in 2015, about one-fifth of which came from coal combustion (UNEP, 2019). Meanwhile, extensive efforts have been devoted to investigating mercury emissions at the national scale, such as in India (Laura et al., 2013), the United States (Pai et al., 2000; Sigler and Lee, 2006), and Europe (Pacyna et al., 2006; Sundseth et al., 2012), which are also coal users and major emitters worldwide. Given China's crucial role in global mercury emissions, numerous efforts were devoted to compiling China's mercury emission inventories for some specific years, such as 1999 (Streets et al., 2005), 2010 (UNEP, 2013), and 2015 (UNEP, 2019), and short-time periods, such as 1980-2007 (Tian et al., 2010), 1978-2014 (Wu et al., 2016), and 2000-2010 (Zhang et al., 2015). It's worth noting that coal was the leading driving force for growing mercury emissions in China. Consequently, to reveal the regional differences in mercury emissions and sectoral details, a few scholars compiled China's detailed atmospheric mercury emission inventories on coal combustion and further analyzed emissions distribution from the perspective of province (Streets et al., 2009; Wang and Luo, 2017) and sector (Liu et al., 2018; Wu et al., 2017). For example, Hui et al. (2017) estimated China's mercury emissions from coal combustion and found out coal-fired power plants were the largest contributors to the reduction of mercury emissions between 2010 and 2017. Therefore, these studies provide insights and guidance for policymakers, regulators, and practitioners to formulate mercury mitigation policies.

Notably, as the center of economic and industrial development, cities are main coal consumers and atmospheric mercury emitters. Therefore, city is an essential implementer of proper mercury reduction policy, while there only exist several initial attempts on mercury emissions estimation in several megacities such as Beijing (Li et al., 2015; Schleicher et al., 2015), Shanghai (Yang et al., 2018), and Chongqing (Yang et al., 2008). For instance, Jiang et al. (2016) compiled an exhaustive inventory for direct mercury emissions in Beijing discussed how to mitigate mercury emissions from

both the local and systematic perspectives. However, an in-depth comparison between the aforementioned city-level mercury emission inventories is difficult as they used inconsistent data sources of various sectors. Moreover, mercury emission profiles for different cities belonging to the same province may vary significantly, due to the discrepancies of the types of APCDs, the application rates of APCDs, the amount of coal burned, etc. As a consequence, it is impractical to use the already existing mercury inventories at the provincial/national/global scale to guide the mercury mitigation actions at the city level, as the inventories at the larger scale hide the aforementioned discrepancies. Regarding this, a comprehensive inventory with higher resolution that reveals the feature of city-specific mercury emission profiles based on a unified coal dataset is in crucial need to support proper and dedicated mercury emission mitigation policies.

To fill the knowledge gap, for the first time, this study presents a comprehensive city-level inventory of mercury emissions from coal combustion of 47 sectors in 2010 for 182 cities and updated the 2015 city-level mercury inventory with the same sectoral resolution for 13 cities. The spatial characteristics of mercury emissions from coal combustion in terms of emission intensities, per capita emissions and key sectors are revealed. Furthermore, the emission uncertainties of each city and mercury speciation distribution are estimated. Last but not least, policy implications for reducing mercury emissions from coal combustion in different cities are elaborated.

2 Materials and methods

2.1 Scope

The mercury emission inventory in this study considers the emissions occurring within the administrative-territorial scope, while the emissions from imported electricity and heat are excluded. The latest energy dataset in 2010 and corresponding emission factors are applied to estimate mercury emissions. The detailed methods are illustrated in the following sections.

2.2 Model description.

Emission factor (EF) is an essential parameter for mercury emission inventory compilation. According to Zhang et al. (2015), coal-related emission sources are classified into 4 categories, namely coal-fired power plants (CFPPs), industrial coal combustion, residential coal combustion, and other coal combustion. Furthermore, the

CFPPs refer to sources including coal combustion for thermal power generation and heating supply. Residential coal combustion represents bulk coal combustion for residential use. The subcategories of industrial coal combustion and other coal combustion are shown in Table A1.

For each category, the EF varies significantly. Generally, EFs can be calculated by using the dynamic technology-based emission factor model (Zhang et al., 2015), as shown in Eq 1.

$$EF = \sum_i \sum_j \left[M_i \cdot \left(1 - f_j \cdot w_j \right) \cdot R_j \cdot \left(1 - \sum_k P_{i,j,k} \cdot \eta_{j,k} \right) \right] \quad (1)$$

where M is mercury content of coal as consumed, R is mercury release rate of a certain type of boiler or technique, f is the rate of the pretreatment of coal, w is mercury removal efficiency of the pretreatment. The average mercury removal efficiency of coal washing is 30.0% (Liu et al., 2018). P is the proportion of different types of APCD combinations, η is mercury removal efficiency of a certain type of APCD combination, i indicates the city number, j is the type of boiler or production process, k is the type of APCD combinations.

With the calculated EF , mercury emissions from coal combustion can be calculated by:

$$E = AL \times EF \quad (2)$$

where E represents the sectoral mercury emission while AL represents the amount of coal burned.

2.3 Data sources

The coal consumption inventory covering 47 sectors of 182 cities (Table A1) in 2010 is derived from Shan et al. (2018). Meanwhile, the coal consumption for 13 cities in 2015 is derived from cities' statistical yearbooks. The data of 182 cities' population, GDP, industrial output and other socioeconomic data are collected from cities' statistical yearbooks and China City Statistical Yearbook 2011.

The mercury content of coal as consumed is obtained from Zhang et al. (2012), shown in Table A2. For CFPPs, this study updates the plant-specific APCD information, based on the official reports issued by the Ministry of Ecology and Environment (MEEPRC, 2014). However, the reports just cover the CFPPs with capacities that are equal to 75% of the national total. For the rest of the CFPPs without exact APCD

information, this study uses the data (installation rates) from Hui et al. (2017). Based on the plant-specific APCD information, this study estimates the city-level APCDs installation rates, shown in Table A3. For industrial coal combustion, the APCDs installation rates of APCDs are derived from Zhang et al. (2015). The mercury removal efficiencies of APCDs and production processes are collected from existing studies (Liu et al., 2018; Wang et al., 2010; Wu et al., 2016; Zhang et al., 2015), summarized in Tables A4 and A5. In addition, the mercury speciation profiles in exhausted gas refer to previous studies (Liu et al., 2018; Wu et al., 2016; Zhang et al., 2015), and the details are shown in Table A6.

2.4 City and sector classification

The coal consumption inventory of each city consists of 47 socioeconomic sectors, of which 39 sectors in industrial coal combustion are divided into 4 categories, namely, 5 energy production sectors, 16 heavy manufacture sectors, 13 light manufacture sectors and 5 high technology sectors (Shan et al., 2018).

To further analyze and compare mercury emissions of different cities, this study takes GDP, the proportion of coal in energy mix and cities' population as the benchmark to classify the cities into various groups. In terms of GDP and industrial outputs, cities are classified into 5 groups: tertiary industry-based cities, high-tech cities, energy production cities, heavy manufacturing cities, and light manufacturing cities (Shan et al., 2018). Based on the proportion of coal in the energy mix, cities are divided into 3 groups: heavily coal-reliant cities, coal-based cities, and other cities. Considering the population, cities are classified into 3 groups: megacities, large cities, and small cities (Cai et al., 2019). The detailed city categories can be found in Table A7.

2.5 Uncertainty analysis

Mercury emission uncertainties are mainly resulted from three input parameters in the inventory models, namely, the amount of coal burned, mercury content of coal and removal efficiencies of APCDs. The Monte Carlo simulation is used to investigate the uncertainties of mercury emission inventory for each city. The statistical distributions of the aforementioned parameters are summarized in Table A8 (Liu et al., 2018; UNEP, 2013; Wu et al., 2016; Zhang et al., 2012; Zhang et al., 2015). This study sets the simulations for 10000 times to estimate the ranges of uncertainty with an 80% confidence interval. The key characteristics of the distribution function include the P10 and P90 values indicating that there is a possibility of 10% and 90% that the actual below corresponding values, respectively. Moreover, this study adopts the P50 value as

the final estimate. The (P10-P50)/P50 and the (P90-P50)/P50 are considered as the lower and upper limits of the uncertainty range.

3 Results

3.1 Mercury emission inventory from coal combustion of 182 cities

Figure 1. Spatial distribution of mercury pollution of 182 Chinese cities in 2010: (a) Mercury emissions, and the top ten cities in terms of mercury emissions are labeled in this map, as well as the composition of their energy consumption, (b) Mercury emissions per GDP for each city, unit: kg/billion RMB, (c) Mercury emissions per capita for each city, unit: g/capita.

The atmospheric mercury emissions of 182 cities from coal combustion in 2010 were estimated to be 202.3 tons, including 137.6tons Hg⁰, 60.4 tons Hg²⁺, and 4.3 tons Hg_p (more details see Supporting Information Table A9). Fig.1 (a) shows that most

eastern coastal cities and some central cities have comparatively higher emissions. Chongqing, Suzhou, Nanyang, Shangqiu, Ordos, Wuhan, Sanmenxia, Shanghai, Baotou, and Handan were the top ten mercury emitters, together responsible for about one-fifth of the total emissions of the 182 cities. It is found that cities with large emissions share two major characteristics: one is the large quantity of power generated by CFPPs (i.e., Ordos, Baotou, Nanyang, Sanmenxia and Shangqiu); and the other is coal dominated energy mix (i.e., Suzhou, Handan, and Chongqing). Besides, the coal-related mercury emission profile is also greatly influenced by the types and applications of APCDs. For instance, although the amount of coal consumed by Handan was similar to that of Ningbo, Handan had 25.0% higher mercury emissions because of its relatively lower installation rate of desulfurization devices in CFPPs (with an average mercury removal rate of 44.5%). Mercury content in coal and the coal pretreatment are also crucial influential factors for city mercury emissions. For example, the amount of coal consumed by Chongqing equaled to about three-quarters of that in Nanyang (the largest city-level coal consumer nationwide in 2010), while its mercury emissions from coal combustion were 1.3 times the emissions from the latter, owing to its high mercury content in coal and extremely low coal washing rate.

Mercury emission intensity, defined as mercury emissions per GDP, varied significantly among all the cities (Fig.1 (b)). Huaibei had the highest emission intensity (44.8 kg/billion RMB), nearly 100 times higher than the lowest one in Karamay (0.5 kg/billion RMB). The strikingly different emission intensities were resulted from different energy structures in each city. The emission intensity of Huaibei where coal occupied an overwhelming 99.1% in its energy mix, was 16.2 times that of Daqing, a famous crude oil producer in China with about three-fourths of its consumed energy coming from oil and nature gas.

The per capita mercury emissions of each city are presented in Fig. 1 (c). The largest per capita emissions were found in Ordos with an amount of 2.44 g/capita, followed by Sanmenxia (1.48g/capita) and Yinchuan (1.26 g/capita). These cities were located in less developed northwestern China with large energy-intensive industries and small population. It is interesting to note that some cities, like Jiayuguan, Tongling, and Wuhai, have large per capita mercury emissions (1.16, 0.82 and 0.81 g/capita, respectively), in contrast to corresponding small emissions amount (0.26, 0.59 and 0.41 tons, respectively).

3.2 Mercury emissions from sectors in city

The 47 sectors in each city were aggregated into 4 types: industrial coal combustion, CFPPs, residential coal combustion, and other coal combustion. Industrial coal combustion and CFPPs were the main contributors to the mercury emissions with the amount of 93.0 and 91.2 tons, respectively, due to their huge coal consumption. Mercury emissions from residential coal combustion and other coal combustion were respectively only 6.9 and 11.2 tons, far lower than that of industrial coal combustion and CFPPs. It should be noted that the amount of coal consumed by industrial coal combustion was 0.73 billion tons less than that of CFPPs, while industrial coal combustion emitted 1.8 tons more mercury. That is because nearly 95% of industrial coal-fired boilers only had wet scrubber (WET) while CFPPs were equipped with wet flue gas desulfurization (WFGD) and electrostatic precipitator or fabric filter (ESP/FF) on large scale to remarkably remove mercury from flue gas in 2010.

Figure 2. Characteristics of atmospheric mercury emissions from industrial coal combustion in 2010: (a) Sectorial mercury emissions (b) Emission-Lorenz curve of 7098 industrial sectors in 182 cities, and (c) The top ten sectors in 182 cities ranked by the amount of mercury emissions (t). (The color of bar represents the sector type, and

the number to the right of the city name indicates a specified sector of this city, which is consistent with the sequence of sectors in Table A1. For example, Jixi (1) in Figure 2 (c) refers to the “Coal Mining and Dressing” sector in Jixi and belongs to the energy production sector.)

This study further lucubrates the emission characteristics of 39 sectors of industrial coal combustion, demonstrated in Fig. 2(a). The largest sectoral mercury emissions (17.2 tons) belonged to *Smelting and Pressing of Ferrous Metals* (Sector 27), as its products were coal-intensive. Similarly, *Nonmetal Mineral Products* (Sector 26) yielded the second-largest emissions (16.8 tons). Subsequently, *Coal Mining and Dressing* (Sector 1) ranked the third with 15.2 tons of mercury emissions due to the wide use of small industrial coal-fired boilers with inefficient APCDs and its large demand for coal. Generally, light and heavy manufacturing sectors had high emission intensities, together contributing to 80% of the total emissions.

Fig. 2 (b) portrays the distribution of mercury emissions among sectors in different cities. Over 90% of the mercury emissions from industrial coal combustion were concentrated in the top 10% sectoral emitters. As shown in Fig.2 (c), *Coal Mining and Dressing* in Huaibei, Chongqing, and Jinzhong occupy the top three places among 7098 industrial sectors, with amounts of 1.8 tons, 1.7 tons and 1.4 tons of mercury emissions, respectively. In coal base cities, these sectors equipped with inefficient industrial coal-fired boilers that consumed large amounts of coal, thus resulting in large mercury emissions.

3.3 Emission characteristics of city clusters

Fig. 3 reveals the characteristics of mercury emissions from coal combustion in different city clusters. From the perspective of energy structure, the 182 cities were categorized as 61 coal-based cities, 52 heavily coal-reliant cities, and 69 other cities, and they contributed to 38.0%, 32.2% and 29.8% of the total mercury emissions, respectively. The coal-based city cluster had the largest total emissions, but the emission distribution was comparatively scattered, ranging from 0.04 tons in Aletai to 6.0 tons in Chongqing. According to different cities’ populations, the 182 cities were divided into three categories, namely 67 large cities, 64 megacities, and 51 small cities. As a large amount of coal was consumed by megacities’ CFPPs to meet the enormous energy demand, the megacities also produced a large amount of mercury emissions (half of the total). From the perspective of manufacturing structure, the 182 cities were classified into 51 heavy manufacturing cities, 67 light manufacturing cities, 32 energy production

cities, 24 high-tech cities, and 8 tertiary industry-based cities, responsible for 28.8%, 29.9%, 18.0%, 15.6% and 7.7% of the total mercury emissions, respectively. Nearly 80% of emissions were attributed to the manufacturing and energy production cities, mainly because their sectoral coal consumers were short of efficient end-of-pipe control measures. Notably, the mercury emissions of tertiary industry-based cities highly concentrated in the range of 1.0 tons to 2.6 tons, due to their similar energy structure and population size.

Figure 3. Emission characteristics of different city clusters in 2010. The violin plot shows the distribution of the data and its probability density. The bottom, band inside and top of the box plot inside the violin plot represent the first, second (medium value) and third quartiles. The scatter plot shows the total emissions of city clusters. The abbreviations in the figure refer to five manufacturing structures (EP-Energy production, HM-Heavy manufacturing, HT-High-tech, LM-Light manufacturing, and TI-Tertiary industry-based cities).

3.4 Updated 2015 mercury emissions for 13 cities.

The atmospheric mercury emissions for the 13 cities in 2015 are presented in Fig.4 (a), consisting of 4 municipalities (Beijing, Shanghai, Tianjin, and Chongqing), 4 provincial capital cities (Shijiazhuang, Wuhan, Zhengzhou, and Guangzhou) the rest of 5 other cities with large mercury emissions (Baotou, Handan, Tangshan, Sanmenxia, and Nanyang). Except for Beijing, the CFPPs and industrial coal combustion were the main contributors to mercury emissions in the other 12 cities. Combining the mercury emission model with the logarithmic mean divisia index (LMDI) model, the emission reduction due to coal consumption (RC) and emission factor (RE) change are quantified, respectively. The total emission reduction (RT) is the sum of RC and RE. More details can be found in the “Methodology on emission reduction analysis” section in the Supporting Information. Fig. 4(b) shows the relative contribution of RC and RE to total

mercury emission changes in the 13 cities during 2010-2015. Except for Shijiazhuang, the rest 12 cities witnessed emission reduction during 2010-2015. Nanyang, Sanmenxia, and Chongqing held the top three positions in terms of the reduced mercury emissions, with a volume of 3.8, 2.2 and 1.6 tons, respectively. For Nanyang and Sanmenxia, the emission reduction driven by the declining coal consumption was estimated at 2.0 and 2.8 tons, respectively, which was much higher than the contribution of the emission factor change. That was because more clean energy such as natural gas and solar energy in these cities were used as substitute for coal power during 2010-2015 (HPDRC, 2017). Different from the situation in Nanyang and Sanmenxia, the emission reduction in Chongqing was mainly attributed to the declining emission factors. In 2015, the results show that nearly 70% CFPPs in Chongqing had installed SCR+ESP+WFGD, which can remove at most 87% mercury in the flue gas, thus its emission factor for CFPPs decreased from 0.08 g/t in 2010 to 0.05 g/t. Notably, some cities like Wuhan, Handan, and Baotou experienced a slight emission reduction during 2010-2015, although the contribution of the coal consumption effect and emission factor effect were both significant. Taking Wuhan as an example, the decreasing emission factor contributed to 2.0 tons emission reduction due to the wider application of WFGD and SCR in the coal-fired boilers, while the reduction was largely offset by the rising coal consumption, leading to a net reduction of 0.7 tons during 2010-2015.

Figure 4. Mercury emissions from coal combustion in 13 important cities: (a) Mercury emissions in 2015, (b) The contributors to mercury emission changes in the 13 cities between 2010 and 2015. RT represents the total emission reduction. RC and RE represent the emission reduction due to coal consumption and emission factor change, respectively.

3.5 Uncertainties in the mercury emission inventory.

Uncertainties for the total emissions as well as emissions from different sources are presented in Fig. 5. The total uncertainty (80% confidence interval) for 182 Chinese cities was estimated to range from -51.7% to 133.6%, including CFPPs (-50.7%, 130.4%), industrial coal combustion (-52.3%, 131.4%), residential coal combustion (-52.9%, 152.2%), and other coal combustion (-54.5%, 166.7%). Mercury content in coal played a major role in the total uncertainty, with a proportion of 73.2%, followed by mercury removal efficiencies of APCDs (20.1%) and the amount of coal consumption (6.7%). Among major emission sources, other coal combustion had the largest uncertainties, because of very limited APCDs installation. In contrast, comparatively larger emitters with smaller uncertainties were industrial coal combustion and CFPPs, whose uncertainties mainly came from mercury removal efficiencies of APCDs.

From the city perspective, the largest uncertainty ranges existed in Zunyi, Guiyang, and Hohhot. In these cities, the significant uncertainties were inherent in residential coal combustion and other coal combustion, owing to the high variation of their mercury contents in coal and very limited APCDs installation in these two emission sources.

Figure 5. Uncertainties of the total emissions and emissions from different sources in 2010

4 Discussion

4.1 Comparisons with existing mercury emission inventories for China.

The comparison between this study with the existing provincial and national mercury emission inventories are summarized in Table 1. The overall emissions as well as sectoral mercury emissions in 2010 calculated in this study vary significantly from the estimation of provincial mercury emissions in the existing studies. Such a difference in mercury emission estimation was mainly attributed to the following reasons.

Table 1 The multi-scale comparison between this study with existing studies

Study	Data	Scale	APCD	Coal consumption (Mt)	Emissions(t)			
					Total	IDCC	CFPPs	R&O
Wu et al. (2016)	NESA	Provincial	National average	-	228.9	99.4	100.8	28.7
Zhang et al. (2015)	NESA	Provincial	National average	2508	233.2	119.7	100.0	34.2
Tian et al.(2015)	NESA	Provincial	Provincial average	2984	332.8	171.0	139.4	29.8
This study	CESA	City	City average	2877	202.3	93.0	91.2	18.1

NESA: National Energy Statistical Agency of China; CESA: City's Energy Statistical Agency of China.

Coal consumption data used in this study was collected from the “energy balance table” from the city’s energy statistical yearbook. However, the coal consumption data

in the aforementioned studies were derived from the National Energy Statistical Yearbook. The coal consumption data from inconsistent data source remains subject to large uncertainty and discrepancy (Guan et al., 2012; Liu et al., 2015), leading to the distinct difference of emission estimation between this study and the previous studies. Concretely, the total amount of coal consumed by the 182 cities collected in this study was 15% higher than the national coal consumption in Zhang et al. (2015). It is worth mentioning that, even based on the same official data source, there was still an obvious gap of 476Mt coal consumption between Zhang et.al and Tian et.al.

Another important source for the differences is the diverse emission factors used in different studies. Taking Sichuan province as an example, the provincial average emission factor of CFPPs was estimated as 0.06 g/t in Wu et al. (2016), while emission factors for cities within Sichuan ranged from 0.04 g/t in Panzhihua to 0.10 g/t in Mianyang according to our study. As a result, the mercury emissions of Mianyang would be substantially underestimated if the aggregated emission factor of Sichuan province was adopted. It should be noted that the city-level emission factors calculated in this study are based on plant-specific APCDs data, which can reflect the real situation for pollution control facilities (APCD types and the corresponding application rate) in the city, while the national average APCDs installation rate was applied in Zhang et al. (2015). Taking Beijing as an example, the present paper shows that the application rate of SCR+ESP+WFGD is 67.5%. However, in Zhang et al. (2015), major APCDs combination in Beijing was considered to be ESP+WFGD with a proportion of 68.8%, while the application rate of SCR in Beijing was immensely underestimated. What's more, Zhang et al. (2015) considered that the WET had been completely eliminated in CFPPs, while in Tian et al. (2015) and this study, the WET was still installed in 1.3% and 0.1% of CFPPs, respectively (details see Supporting Information Figure A6).

4.2 Policy implications

Cities are considered as the implementers of the energy-saving and emission-reduction policies, indicating that the provincial and national pollution mitigation heavily depends on policies formulated at the city level (Liu et al., 2019; Wang et al., 2019). However, if the city-level mercury mitigation strategies were formulated based on the previous provincial or national which hide the heterogeneities among city-level mercury emission profiles, it is highly possible that the effectiveness and practicability of the mitigation strategies will be undermined. Even worse, the city-level policies may be misled. Taking the cities in Jiangsu province as an example, CFPPs in Nanjing and

Suzhou have widely been equipped with WFGD to remove mercury. But for some cities like Yancheng and Liaoyuan, the dust removal devices with low mercury removal efficiencies still played a central role in their CFPPs. In this case, using the provincial average mercury emission factors will inevitably lead to overestimation for cities like Suzhou but underestimation for cities like Yancheng. The inaccurate estimation will result in an embarrassing situation, i.e., cities with overestimated emissions may receive excessive and redundant efforts while those with underestimated emissions may fail to meet the mitigation target due to the lack of mitigation inputs. As the current study calculated the accurate city-level energy-related mercury emissions by collecting precise information such as the APCD installation rate for each city, it provides more targeted and precise information for air pollution control policy design.

Based on emission characteristics and energy structure of 182 cities, specific emission reduction actions can be designed for different types of cities. Coal-based cities (e.g., Shijiazhuang and Baotou) and heavily coal-reliant cities (Ordos and Shangqiu), accounting for more than 70% of the total mercury emissions in 2010, are still the priorities in China's mercury mitigation policies. For cities where coal took share of over 70% in the energy mix, like Taiyuan and Nanyang, energy structure adjustment via clean energy substitution is one of the necessary solutions to mercury emission reduction. For instance, the natural gas consumption in Nanyang has increased by 158% while the coal consumption decreased by 49% in 2015 compared with 2010, which helps avoid mercury emissions from coal combustion. In addition, as the important coal base in China, Jinzhong, Huainan should make better use of the by-product (hydrogen) during the coking process and facilitate the development of clean fuel such as hydrogen energy. As the coastal cities with abundant offshore wind resources, Tangshan and Shantou can enhance financial investment to support the development and deployment of offshore wind technologies (Li et al., 2019). Notably, Beijing reduced 0.68 tons mercury emissions in 2015 compared with 2010 by outsourcing the electricity production to nearby regions, such as Ordos and Baotou, suggesting that mercury pollution from electricity production has been transferred to these cities. Therefore, a regional collaborative pollution control is also in badly need, such as establishing an ecological compensation fund to promote the development of solar photovoltaic and wind Power in Ordos and Baotou (Li et al., 2018).

Coal-reliant cities lack of enough efficient end-of-pipe mercury removal devices has great potential in mercury mitigation, if the application rate of APCDs such as

SCR/SCNR increases. A successful case is Chongqing. Its application rate of SCR+ESP+WFGD with the mercury removal efficiency of 70% has increased by 68.7% in 2015 compared with the 2010 level, which leads to a remarkable mercury emission reduction (0.67 tons). However, this study found that the installation proportion of SCR in Nanyang and Sanmenxia and WFGD in Jincheng and Benxi was less than 10% up to 2015, far lower than the national average level. These cities should further upgrade the air pollution control facilities under the supervision of the local government. In addition, cities with high mercury content in coal should promote pretreatment technologies such as coal washing, which can remove about 30% of mercury in coal (Liu et al., 2018). For example, the coal washing rate in Liuzhou and Guiyang is far below the government target (70%), and it deserves more attention (SCPRC, 2013).

The inventory in this study also reveals the detailed sectoral mercury emissions in each city and identifies some key sectoral emitters, which should be the key targets in mercury mitigation strategies. Specifically, Coal Mining and Dressing in Huaibei, Chongqing, Jinzhong contribute more than 60% of the city's mercury emissions. The local governments should promote clean mining technology and impose restrictions on mining and burning of coal with high heavy metal concentrations (Zhu et al., 2016). As the largest industrial city in Guangxi province, the Smelting and Pressing of Ferrous Metals sector in Liuzhou accounts for 61 percent of the city's emissions. For such heavy manufacturing cities, local government should endeavor to phase out excessive capacity and innovating the pollution control devices (Wu et al., 2017). In the long run, heavy manufacturing cities (e.g., Zhengzhou and Luoyang) should accelerate structural transformation and raise the proportion of tertiary and high-tech industries. For instance, as one of the four great ancient capitals of China, Luoyang can promote the sustainable development of cultural tourism and service.

4.3 Limitations and future work

In general, compared to other researches at larger scales, the mercury emission inventory at the city level can provide a more comprehensive and clear picture of regional mercury pollution. However, there are some limitations to this study. First, the city-level emission inventory has large uncertainties, as the precise city-level information such as mercury contents in coal and coal transport matrix is still lacking. To improve the accuracy of the cities' emission inventories, more precise information on mercury content in coal, the types of APCDs, and the application rates of mercury

control devices is in urgent need. Second, this study only compiled the mercury emission inventory in one year, which failed to draw the dynamic and long-term changes in mercury emissions. A long time-series mercury emission inventories with the consistent sectoral resolution at the city level should be developed in future works to draw the evolution trend and identify the driving factors.

5 Conclusion

This study for the first time compiled a high-resolution inventory on atmospheric mercury emissions from coal combustion in China, based on the latest energy dataset and updated emission factors. The total atmospheric mercury emissions from coal combustion were estimated to be 202.3 tons in 2010, with uncertainty ranging from -51.7% to 133.6%. Chongqing, Suzhou, and Nanyang were identified as the top emitters among all the cities, due to their coal dominant energy mix and low installation rates of APCDs that can efficiently remove mercury from flue gas. Moreover, this study categorized all the 182 cities into three groups, according to their energy structures, manufacturing structures, and population. From the sectoral perspective, more than half of the mercury emissions from industrial coal combustion were attributed to *Smelting and Pressing of Ferrous Metals, Nonmetal Mineral Products, and Coal Mining and Dressing*. Moreover, the LMDI decomposition method was applied to analyze the emission reduction in 13 important cities and quantify the contribution of coal consumption and emission factor change during 2010-2015. Finally, based on the results in this study, comprehensive and dedicated mitigation strategies for different types of cities were elaborated according to the characteristics of mercury emissions in different cities.

Supporting information

The mercury emission sources, the methods of emission estimations, sector and city classifications, and uncertainty analysis, corresponding parameters, and the discussion are available in Supporting Information.

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